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1. Your reference — SP 2022

2. Patent application number *(The Patent Office will fill in this part)* — 0317952.0 — 31 JUL 2003

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*
Southampton Photonics Ltd
Phi House
Enterprise Road
Chilworth Science Park
Southampton
SO16 7NS

Patents ADP number *(if you know it)* — 7894330002

If the applicant is a corporate body, give the country/state of its incorporation — UK

4. Title of the invention
Apparatus for Providing Optical Radiation

5. Name of your agent *(if you have one)*
"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*
Graham Jones + company
77 Beaconsfield Road
Blackheath
LONDON
SE3 7LG

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Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

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Number of earlier application	Date of filing *(day / month / year)*

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Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	

11. I/We request the grant of a patent on the basis of this application.

Signature MPVal Date July 31 2003

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Apparatus for Providing Optical Radiation

Field of Invention

This invention relates to an apparatus for providing optical radiation. The invention has particular relevance for high-power fibre lasers, and for welding, drilling, cutting and marking applications.

Background to the Invention

Fibre lasers are increasingly being used for materials processing applications such as welding, cutting and marking. Their advantages include high efficiency, robustness and high beam quality.

Traditional lasers used for material processing applications predominate at around 1.06μm and longer wavelengths such as provided by a carbon dioxide laser (10.6μm). These lasers are being supplemented by fibre lasers operating at around 1.06μm.

High power fibre lasers are often single mode and are often pumped at high intensity levels. If insufficient optical power is provided to saturate the gain medium, very high inversion levels can result leading to self Q-switching effects. The result can be catastrophic failure of the optical fibre gain medium or other optical components within the laser. This can be a particular problem with high-power Q-switched lasers and with master oscillator power amplifiers. It is also a problem for materials processing systems which require very high reliability for 24 hour 7 days per week operation.

An aim of the present invention is to provide an apparatus for providing optical radiation that reduces the above aforementioned problem.

Summary of the Invention

According to a non-limiting embodiment of the present invention, there is provided apparatus for providing optical radiation which apparatus comprises a first amplifier and a first gain controller, in which the first gain controller is configured to limit the intensity of the optical radiation.

The apparatus may be defined by an optical damage intensity, and in which the first gain controller is configured to limit the intensity of the optical radiation below the optical damage intensity. This aspect of the invention is particularly useful in high power amplifiers and lasers which are found to fail catastrophically if pumped without the presence of a sufficient saturating signal. Examples include high energy Q-switched lasers in which feedback is reduced while the Q-switch is off and the cavity Q-factor is extremely low. The inversion builds up and the laser can generate giant pulses due to self Q-switching leading to catastrophic failure. This problem has not hitherto been addressed and is only now becoming important with the emergence of high power optical fibre lasers and amplifiers for aerospace and materials processing applications.

The apparatus may be in the form of a Q-switched laser in which the first amplifier forms part of the Q-switched laser.

The first gain controller may comprise a first cavity within the first amplifier.

The first cavity may be defined by a first threshold inversion, and the Q-switched laser may be defined by a Q-switched threshold inversion, and in which the first threshold inversion is higher than the Q-switched threshold inversion.

The first amplifier may be characterised by an inversion corresponding to the optical damage intensity, which inversion is greater than the first threshold inversion.

The first gain controller may comprise an optical source. The optical source may be a laser diode, a distributed feedback laser diode, a distributed Bragg reflector laser diode, or a fibre laser. The wavelength of the optical source may be different from the wavelength of the optical radiation. The optical source may be used to clamp the inversion of the Q-switched laser so that it does not reach the inversion corresponding to the optical damage intensity.

The apparatus may be in the form of a master oscillator power amplifier comprising a seed laser, and an optical amplifier.

The seed laser may contain the first gain controller. The seed laser may be a Q-switched laser according to present invention. The output of the first gain controller may clamp the inversion of the optical amplifier.

The apparatus may be in the form of an amplifier in which the first gain controller comprises a cavity. The amplifier may comprise an optical fibre characterised by an inversion and in which the cavity clamps the inversion.

The apparatus may be in the form of an amplifier, in which the first gain controller comprises a laser. The amplifier may comprise an optical fibre characterised by an inversion, and the laser clamps the inversion.

The apparatus may be configured to emit greater than 1W of optical power. The apparatus may be configured to emit greater than 5W of optical power.

The apparatus may be configured to emit at least one optical pulse greater than 0.1mJ. The apparatus may be configured to emit at least one optical pulse greater than 1mJ.

The apparatus may be in the form of a master oscillator power amplifier comprising a seed laser and a power amplifier.

The seed laser may be a Q-switched laser according to the invention.

The seed laser may be a semiconductor laser, a distributed feedback laser, a distributed Bragg reflector laser, or a fibre laser.

The power amplifier may be an amplifier according to the invention.

The apparatus may be in the form of a materials processing system.

The apparatus may comprise a plurality of seed lasers at different wavelengths, a multiplexer for combining the outputs of the seed lasers, and a power amplifier. The seed lasers may be configured to output at different wavelengths. The multiplexer may be a wavelength division multiplexer.

The apparatus may comprise a demultiplexer and a plurality of scanners. The seed lasers may be operated in synchronism with the scanners.

The apparatus may include a control circuit to shape the optical radiation to a desired temporal characteristic.

The apparatus may emit optical radiation in substantially a single spatial mode or a plurality of spatial modes.

Brief Description of the Drawings

Embodiments of the invention will now be described solely by way of example and with reference to the accompanying drawings in which:

Figure 1 shows an apparatus for providing optical radiation according to the present invention;

Figure 2 shows an apparatus in the form of a Q-switched laser;

Figure 3 shows the variation of inversion with time in a Q-switched laser;

Figure 4 shows the optical output of a Q-switched laser;

Figure 5 shows the output of the first gain controller with time;

Figure 6 shows variation of inversion with time in a Q-switched laser that has been gain clamped;

Figures 7 shows the optical output of a Q-switched laser that has been gain clampled;

Figure 8 shows the output of the first gain controller with time from a Q-switched laser that has been gain clamped;

Figure 9 shows apparatus in the form of a Q-switched laser in which the first gain controller comprises an optical source;

Figure 10 shows apparatus in the form of a master oscillator power amplifier;

Figure 11 shows apparatus in the form of an optical amplifier that comprises a cavity;

Figure 12 shows apparatus in the form of an optical amplifier that comprises an optical source;

Figure 13 shows apparatus in the form of a master oscillator power amplifier; and

Figure 14 shows apparatus in the form of a materials processing system comprising a plurality of seed lasers.

Detailed Description of Preferred Embodiments of the Invention

With reference to Figure 1, there is provided apparatus for providing optical radiation 3 which apparatus comprises a first amplifier 1 and a first gain controller 2, in which the first gain controller 2 is configured to limit the intensity of the optical radiation 3..

Figure 2 shows apparatus in the form of a Q-switched laser 20 which contains the first amplifier 1 and the gain controller 2. The first amplifier 1 is an optical fibre amplifier comprising a pump 21, a pump coupler 22, and a rare-earth doped fibre 23. The pump 21 can be a fibre laser, a semiconductor laser diode, or a module comprising a plurality of semiconductor laser diodes, and the rare-earth doped fibre 23 can comprise an optical fibre doped with ytterbium, erbium, thulium, neodymium or holmium, or co-doped with one or more of these rare-earth ions, such optical fibre being operated as a two, three or four level laser system. The pump coupling arrangement can either be based on core pumping or cladding pumping. The Q-switched laser 20 also comprises an optical switch 24, and first and second reflectors 25, 26. The optical switch 24 can be an acousto-optic modulator, a Pockels cell or a Kerr cell, and the first and second reflectors 25, 26 can be gratings, fibre Bragg gratings, dichroic mirrors, or other reflectors commonly used in waveguide lasers. The first gain controller 2 comprises a first cavity 27 within the first amplifier 1. The first cavity 27 is formed by two reflectors 28 which can be fibre Bragg gratings. The first cavity 27 is configured to lase at a different wavelength than the wavelength of the optical radiation 3 by appropriate selection of the reflectors 28.

Figure 3 shows the inversion 33 of the rare-earth doped fibre 23 as a function of time 34 during low-power operation. (Note that more exactly, Figure 3 shows the average inversion 33 as the inversion may vary along its length). Four inversions are

shown, namely a maximum inversion 30 Nmax, a first cavity inversion 31 Nc, a Q-switched threshold inversion 32 Nthr, and an inversion 35. The maximum inversion 30 Nmax corresponds to the maximum inversion that can be achieved by pumping the Q-switched laser 20 with the pump 21 with the switch OFF and with no feedback from reflector 25 and without the presence of the first cavity 27. The first cavity inversion 31 Nc corresponds to the first threshold, namely the threshold of the laser formed by the first cavity 27. The Q-switched threshold inversion 32 Nthr corresponds to the Q-switched threshold, namely the average threshold for the Q-switched laser 20 at a given pulse repetition rate. The inversion 35 corresponds to the inversion within the Q-switched laser at which optical damage occurs within the apparatus, namely the optical damage intensity 72 which is described with reference to Figure 7.

Figure 4 shows the output pulse train 40 from the Q-switched laser 20 and Figure 5 shows the output 50 from the first cavity gain controller 2 with time (in this case the first cavity 27). The output 50 is zero because the inversion 33 never reaches the first cavity inversion 31 Nc.

Figure 6 shows the threshold 33 for the Q-switched laser 20 achieved for either higher power pumping or lower repetition rate. The threshold 33 is clamped periodically at the first cavity threshold 31 Nc. When the Q-switch 24 is turned on, the Q-switched laser 20 emits the pulses 70 shown in Figure 7, and the inversion 33 falls. The pulses 70 have a peak intensity 71. Figure 8 shows the output 50 of the first gain controller 2 (in this case the first cavity 27) which comprises pulses 80 which occur when the inversion 33 has reached the first cavity threshold 31 Nc.

The presence of the first cavity 27 within the Q-switched laser 20 can be seen to have limited the inversion 33 and hence the intensity 71 of the optical radiation 3.

This is especially useful for high-power applications for limiting the intensity 71 of the optical radiation 3 such that it is below the optical damage intensity 72 of the apparatus. This aspect of the invention relies upon the first threshold inversion 31 being higher than the Q-switched threshold inversion 32, and the inversion 35 shown with reference to Figures 3 and 6 corresponding to the optical damage intensity 72 being higher than the first threshold 31. By high-power applications it is meant applications in which the intensity of the optical radiation 3 within the optical fibre 23 approaches or exceeds the optical damage thresholds of the components within the apparatus. Experimentally, optical damage has been observed in silica optical fibres at intensities above $1GW/cm^2$, and the apparatus is believed to be very useful for intensities above $1GW/cm^2$ and even more so for intensities above $5GW/cm^2$. In typical single mode laser systems, these intensities can correspond to pulse energies greater than 0.1mJ and 0.5mJ respectively, and average output powers greater than around 1W and 5W respectively.

Figure 9 shows apparatus in the form of a Q-switched laser 90 in which the first gain controller 2 comprises an optical source 91 and a coupler 92. The optical source 91 can be a laser diode, distributed feedback laser diode, a distributed Bragg reflector laser diode, or a fibre laser. The operation of the Q-switched laser 90 is similar to the operation of the Q-switched laser 20 with the inversion 33 of the first amplifier 1 being clamped by optical radiation from the optical source 91. The optical wavelength of the optical source 91 must be different from the wavelength of the optical radiation 3 and selected to clamp the inversion 33 of the first amplifier 1 at the first threshold 31 Nc. The optical source 91 can be operated continuous wave, modulated, or pulsed. However it is important that the optical source 91 is clamping

the Q-switched laser to prevent the inversion 33 reaching the inversion 35 corresponding to the optical damage intensity 72.

Figure 10 shows apparatus in the form of a master oscillator power amplifier MOPA 100 comprising a seed laser 101, an optional isolator 102, and an optical amplifier 103. The seed laser 101 comprises the gain controller 2. The seed laser 101 can be the Q-switched laser 20 with the optical output 50 being used to clamp the inversion of the optical amplifier 103. The seed laser 101 can also be the Q-switched laser 90 with the optical source 91 configured to co-propagate with output radiation 3 rather than counter propagate as shown in Figure 9. The isolator 102 can be an optical isolator, an optical circulator, a polariser, an optical switch, an acousto-optical modulator, or an electro-optic modulator such as a Pockels cell or Kerr shutter.

Figure 11 shows apparatus in the form of an amplifier 110 in which the first gain controller 2 comprises a cavity 112. The cavity 112 clamps the inversion of the optical fibre 23 in a similar way as described with reference to Figure 2.

Figure 12 shows apparatus in the form of an amplifier 120 in which the first gain controller 2 comprises the laser 91 and the coupler 92. The first gain controller 2 clamps the inversion of the optical fibre 23 in a similar way as described with reference to Figure 9.

The amplifiers 110 and 120 are useful for high-power and high-energy applications (>1W or >0.1mJ pulses) in which an input signal 113 of sufficient intensity to prevent optical damage cannot be guaranteed (for example in power-on and power-off modes, power interruption, or cable disconnection).

Figure 13 shows apparatus in the form of a master oscillator power amplifier MOPA 130 comprising a seed laser 131, the optical isolator 102, and a power amplifier 133. The seed laser 131 can be the Q-switched lasers 20 or 90, and the

power amplifier 133 can be the amplifiers 110 or 120. Alternatively the seed laser 131 can be a semiconductor laser, a distributed feedback laser, a distributed Bragg reflector laser, or a fibre laser. At least one of the seed laser 131 and power amplifier 133 contains the first gain controller 2.

Figure 14 shows apparatus in the form of a materials processing system 140 comprising a plurality of seed lasers 131, a multiplexer 142, a first amplifier 143, a power amplifier 144, a demultiplexer 145, a plurality of scanners 146, a detector 147, and control circuitry 148. The seed lasers 131 can emit at the same wavelength or at different wavelengths. The apparatus is shown with seed lasers 131 emitting at different wavelengths, their output powers being combined by the multiplexer 142 which can be a wavelength division multiplexer, and the combined signal being amplified by the first amplifier 143 and the power amplifier 144. At least one of the first and power amplifiers 143, 144 can be the amplifiers 110 or 120. The output from the power amplifier 144 is demultiplexed by the demultiplexer 145 which can be a bulk optic grating separating the different wavelengths to different scanners 146 which direct energy to the work pieces 1410. Depending upon the configuration of the apparatus, there may be a clamping signal 1411 used to limit the output power of a component within the apparatus. This can be filtered out by the demultiplexer 145 as shown. The apparatus can include control circuitry 148 to control the signals from the seed lasers 131 in synchronism with the scanners 146. This is especially useful in high-throughput laser marking systems in which the same mark is applied to many similar items. Optical feedback can be provided with an optical tap 149 and a detector 147. The optical tap 149 can comprise a beam splitter. Preferably, the optical tap 149 provides information about each wavelength in the system. Alternatively or in addition, there can be provided a plurality of optical taps 149 (not

shown) located between the demultiplexer 145 and each scanner 146 in order to provide information on each wavelength. The controller 148 may also be used to shape the optical radiation 3 to a desired temporal characteristic 1414 such as a waveform 1412 with substantially rectangular pulses 1413. The apparatus may include a detector (not shown) to feedback the shape of the optical radiation 3 to the control circuit 148.

Examples of the apparatus have been described with reference to optical fibre amplifiers. These examples can be applied to lasers and amplifiers generally such as diode-pumped solid state lasers, semiconductor lasers, waveguide lasers, and planar-waveguide lasers. The apparatus can include lasers that output in a single spatial mode or in a plurality of spatial modes. The apparatus shown with reference to Figure 14 can be used with a single scanner, and comprise a single laser of the form shown with reference to Figures 1 to 13.

It is to be appreciated that the embodiments of the invention described above with reference to the accompanying drawings have been given by way of example only and that modifications and additional components may be provided to enhance performance.

The present invention extends to the above-mentioned features taken in isolation or in any combination.

Claims

1. Apparatus for providing optical radiation which apparatus comprises a first amplifier and a first gain controller, in which the first gain controller is configured to limit the intensity of the optical radiation.

2. Apparatus according to claim 2 wherein the apparatus is defined by an optical damage intensity, and in which the first gain controller is configured to limit the intensity of the optical radiation below the optical damage intensity.

3. Apparatus according to claim 1 or claim 2 in the form of a Q-switched laser in which the first amplifier forms part of the Q-switched laser.

4. Apparatus according to claim 3 in which the first gain controller comprises a first cavity within the first amplifier.

5. Apparatus according to claim 4 in which the first cavity is defined by a first threshold inversion, and the Q-switched laser is defined by a Q-switched threshold inversion, and in which the first threshold inversion is higher than the Q-switched threshold inversion.

6. Apparatus according to claim 5 in which the first amplifier is characterised by an inversion corresponding to the optical damage intensity, which inversion is greater than the first threshold inversion.

7. Apparatus according to claim 3 in which the first gain controller comprises an optical source.

8. Apparatus according to claim 7 in which the optical source is a laser diode, a distributed feedback laser diode, a distributed Bragg reflector laser diode, or a fibre laser.

9. Apparatus according to claim 8 in which the wavelength of the optical source is different from the wavelength of the optical radiation.

10. Apparatus according to claim 9 in which the optical source is used to clamp the inversion of the Q-switched laser so that it does not reach the inversion corresponding to the optical damage intensity.

11. Apparatus according to claim 1 or claim 2 in the form of a master oscillator power amplifier comprising a seed laser, and an optical amplifier.

12. Apparatus according to claim 11 in which the seed laser contains the first gain controller.

13. Apparatus according to claim 12 in which the seed laser is a Q-switched laser according to any one of claims 3 to 10.

14. Apparatus according to claim 13 in which the output of the first gain controller clamps the inversion of the optical amplifier.

15. Apparatus according to claim 1 or claim 2 in the form of an amplifier in which the first gain controller comprises a cavity.

16. Apparatus according to claim 15 in which the amplifier comprises an optical fibre characterised by an inversion and in which the cavity clamps the inversion.

17. Apparatus according to claim 1 or claim 2 in the form of an amplifier, in which the first gain controller comprises a laser.

18. Apparatus according to claim 17 in which the amplifier comprises an optical fibre characterised by an inversion, and the laser clamps the inversion.

19. Apparatus according to any one of the preceding claims in which the apparatus is configured to emit greater than 1W of optical power.

20. Apparatus according to claim 19 in which the optical power is greater than 5W.

21. Apparatus according to any one of the preceding claims in which the apparatus is configured to emit at least one optical pulse greater than 0.1mJ.

22. Apparatus according to claim 21 in which the optical pulse is greater than 1mJ.

23. Apparatus according to claim 1 or claim 2 in the form of a master oscillator power amplifier comprising a seed laser and a power amplifier.

24. Apparatus according to claim 23 in which the seed laser is a Q-switched laser according to any one of claims 3 to 10.

25. Apparatus according to claim 23 in which the seed laser is a semiconductor laser, a distributed feedback laser, a distributed Bragg reflector laser, or a fibre laser.

26. Apparatus according to any one of claims 23 to claim 24 in which the power amplifier is an amplifier according to any one of claims 15 to 18.

27. Apparatus in the form of a materials processing system comprising at least one apparatus according to claims 1 to 26.

28. Apparatus according to claim 27 which apparatus comprises a plurality of seed lasers at different wavelengths, a multiplexer for combining the outputs of the seed lasers, and a power amplifier.

29. Apparatus according to claim 28 in which the seed lasers output at different wavelengths and in which the multiplexer is a wavelength division multiplexer.

30. Apparatus according to claim 29 and further comprising a demultiplexer and a plurality of scanners.

31. Apparatus according to claim 30 in which the seed lasers are operated in synchronism with the scanners.

32. Apparatus according to any one of claims 27 to 31 and including a control circuit to shape the optical radiation to a desired temporal characteristic.

33. Apparatus according to any of the preceding claims in which the apparatus emits optical radiation in substantially a single spatial mode.

34. Apparatus according to any one of claims 1 to 32 in which the apparatus emits optical radiation in a plurality of spatial modes.

35. Apparatus substantially as herein described with reference to the accompanying drawings.

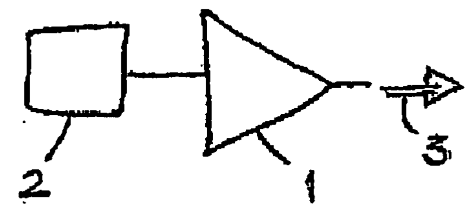


FIG 1

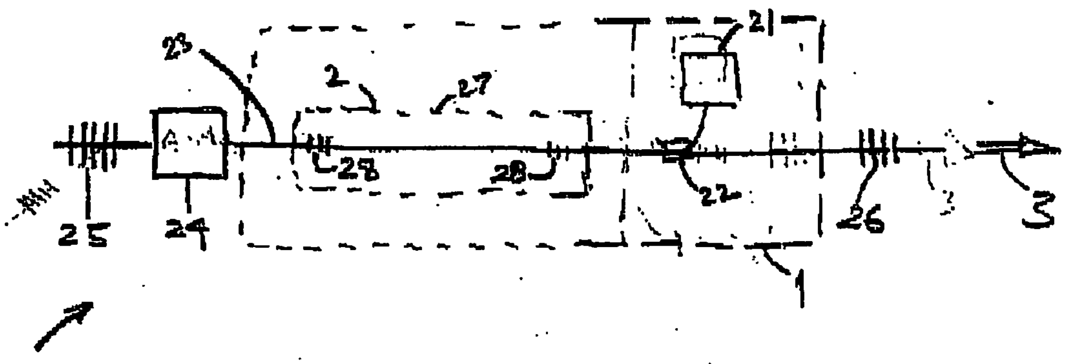


FIG 2

FIG 3

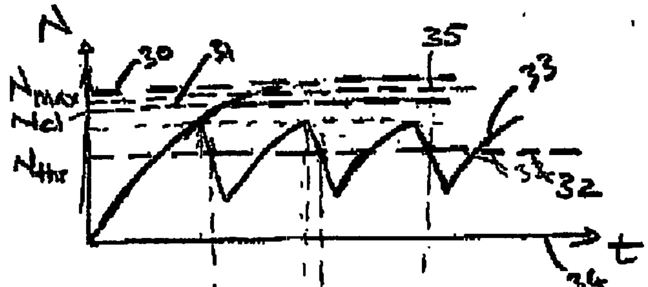
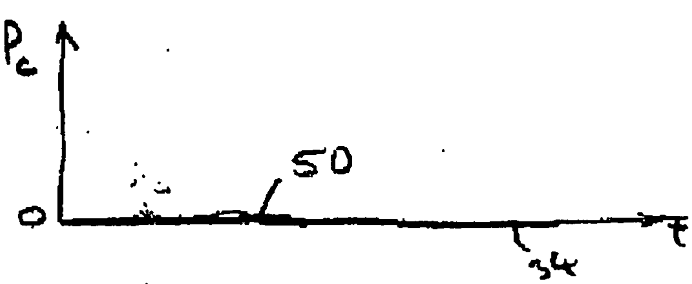


FIG 4

FIG 5



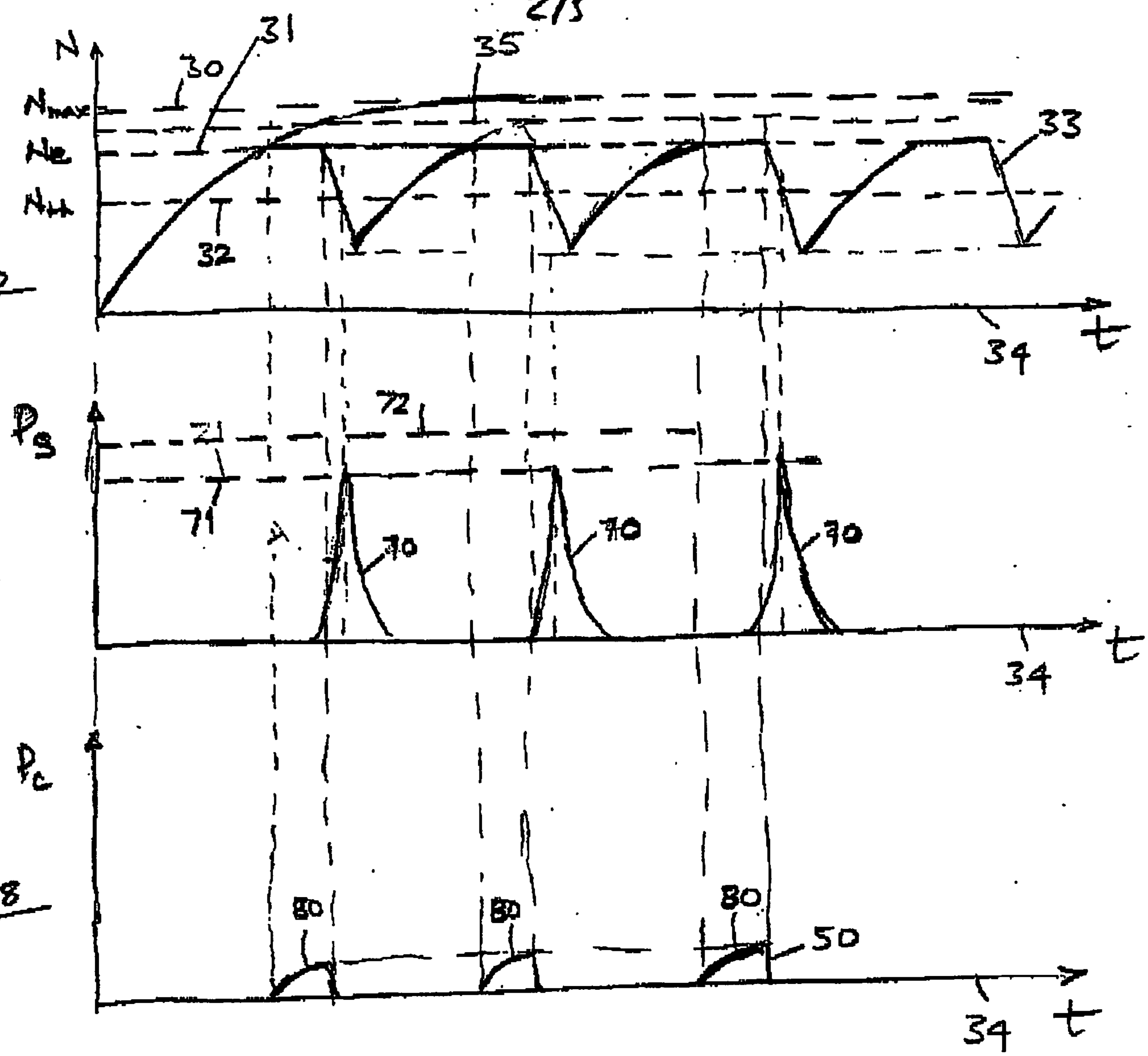


FIG 6

FIG 7

FIG 8

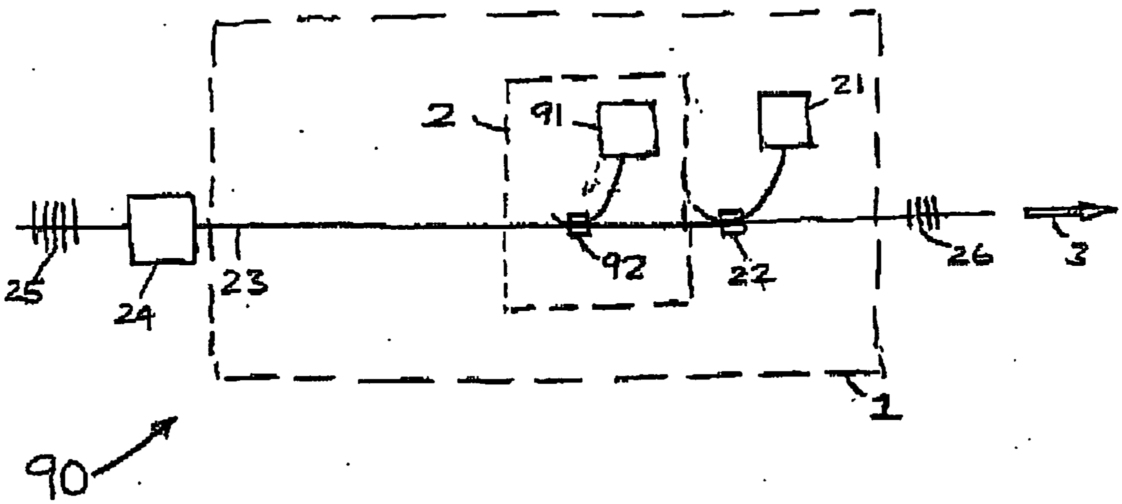


FIG. 9

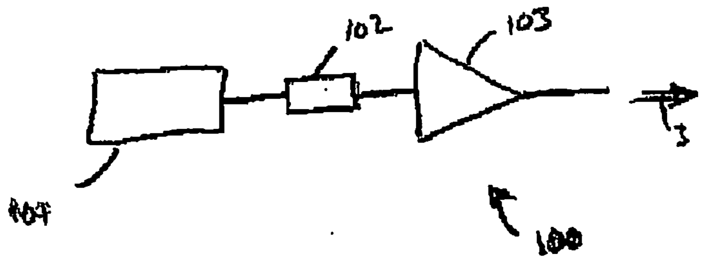


FIG. 10

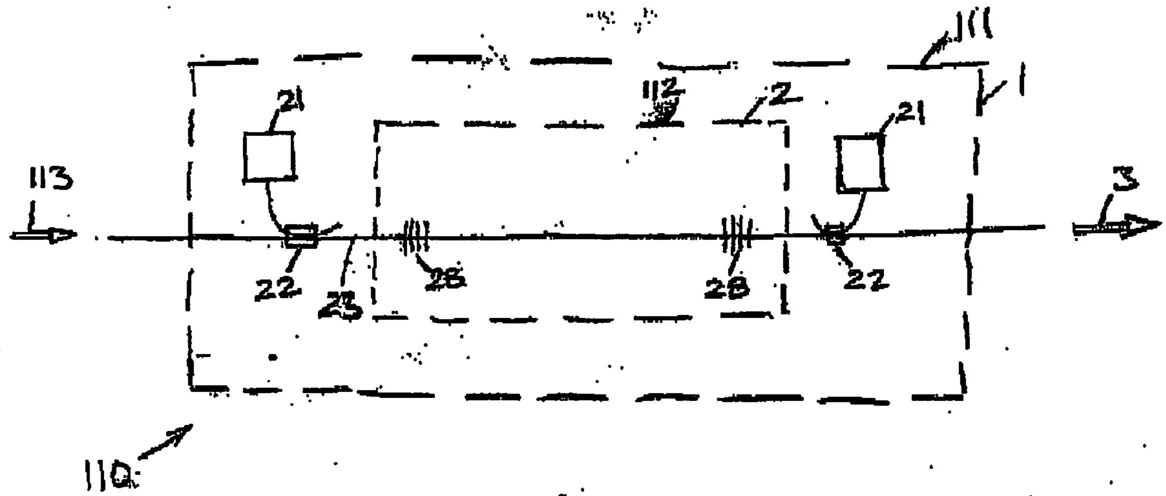


FIG 11

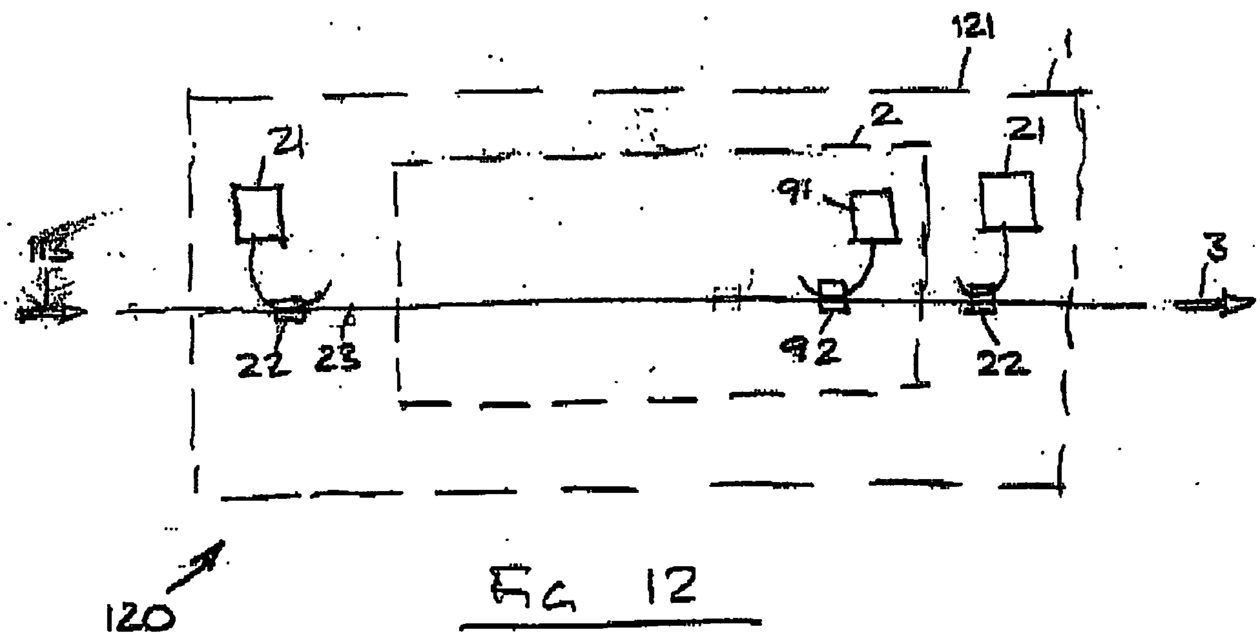


FIG 12

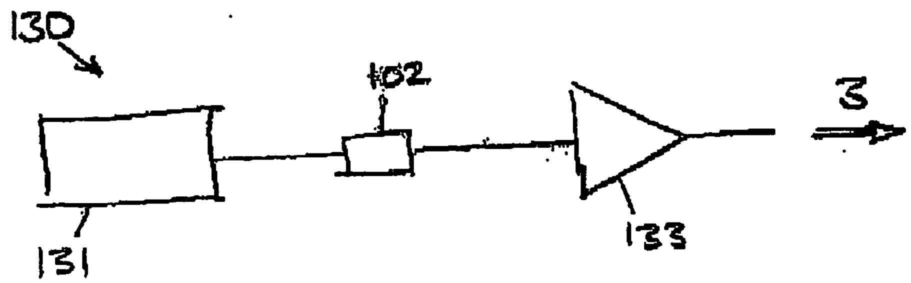

130
102
3
131
133

FIG 13

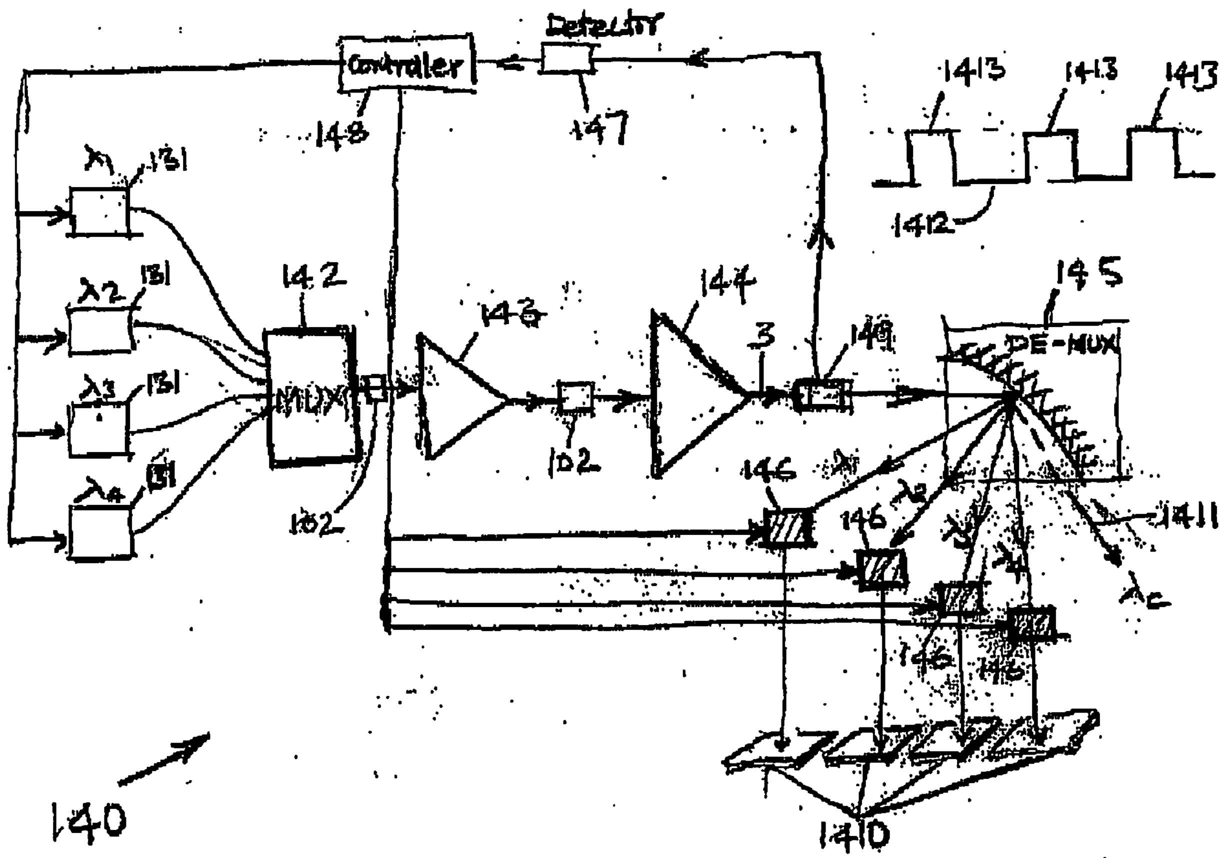

Detector
Controller
148
147
1413
1413
1413
1412
λ1
λ2
λ3
λ4
131
142
MUX
143
144
3
149
145
DE-MUX
102
102
146
146
146
146
1411
λc
1410
140

FIG. 14